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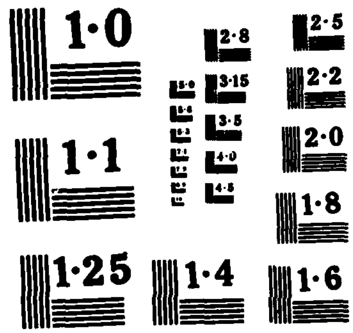

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FOREIGN TECHNOLOGY DIVISION

THE PHYSICS AND TECHNOLOGY OF STRONG MAGNETIC FIELDS

(Chapter 10)

by

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Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*<u>ye</u> initially, after vowels, and after ъ, ь; <u>e</u> elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

Chapter 10. CONCENTRATION OF THE MAGNETIC FIELD

The gaseous nitrogen under high pressure enters from the cylinders into the central tube 5 from below and squeezes the liquid 6 (sodium-potassium alloy) from the lower tank along the ring peripheral channel 7 upward. The liquid passes through holes 8 in the external wall of the hydromagnet, enters into the working chamber, and through holes 9 in the internal wall emerges into the central tube 10; then it is guided into the upper tank 11. After the basic mass of liquid is found upward, the nitrogen cylinders are disconnected, and both chambers, the upper and lower, are connected with the atmosphere. The pressure is equalized, and the liquid overflows through the special small hole back into the lower chamber. Then the cycle is repeated.

The hydromagnet operated in a pulse mode with a pulse duration of about 0.5 s. The induced magnetic field was measured by a test coil, which is located in the center of the hydromagnet. The obtained strength of the induced magnetic field (1.9 kOe) is in good agreement with that computed theoretically (2.1 kOe). The small divergence is connected, apparently, with the fact that the pressure in the hydromagnet system was less than that measured on a manometer on cylinders with the nitrogen.

§ 3. Method of explosion

The idea of intensifying the magnetic field because of the energy released during an explosion was first advanced by Ya.P. Terletskiy [6]. He solved the problem of the attenuation of the currents induced in the conducting sphere and found that the attenuation occurs exponentially with the time of relaxation

$$\tau = \frac{4\pi}{c^2} \alpha R^2 \sigma, \qquad (10.27)$$

where R is the radius of the sphere, σ - the specific electroconductivity of the sphere, and α - the shape factor, which has an order of unity. For a copper sphere with a diameter of 10 cm, the

relaxation time, calculated according to formula (10.27), exceeds 1 cm.

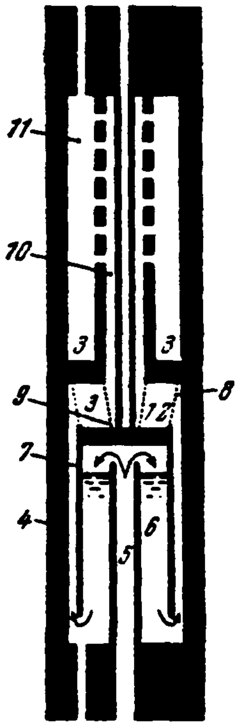


Fig. 66.

If we subject the sphere to comprehensive compression for the time much less than the relaxation time, then it will be conducted as a body with an infinite conductivity. If toward the beginning of compression the magnetic flow Φ_0, penetrated the sphere, then it is "frozen" into it, and the magnetic field strength is increased with compression.

Actually, the rate of change of the induction flow included into the shell moving at velocity $\boldsymbol{v}$ is equal to

$$\frac{d\Phi}{dt}=\int_S\left[\frac{\partial \boldsymbol{B}}{\partial t}+(\operatorname{grad}\boldsymbol{B})\boldsymbol{v}+\operatorname{rot}[\boldsymbol{B}\boldsymbol{v}]\right]dS. \qquad (10.28)$$

Considering that

$$\operatorname{rot}\boldsymbol{E}=-\frac{\partial \boldsymbol{B}}{\partial t},\quad \operatorname{rot}\boldsymbol{B}=\frac{\partial \boldsymbol{E}}{\partial t},\quad \boldsymbol{E}[\boldsymbol{v}\boldsymbol{B}]=0 \quad (\sigma=\infty), \qquad (10.29)$$

we find that $\frac{d\Phi}{dt}=0$ and $\Phi=\text{const.}$

Since the magnetic flow is retained with compression of the shell, then the magnetic field strength is increased inversely

proportional to the square of its linear dimensions R (index 0 refers to the initial position):

$$B = B_0\left(\frac{R_0}{R}\right)^2. \tag{10.30}$$

The change in the magnetic energy with compression

$$\frac{E_m}{E_{m0}} = \frac{R_0}{R}. \tag{10.31}$$

With deformation of the cylinder

$$\frac{E_m}{E_{m0}} = \left(\frac{R_0}{R}\right)^2. \tag{10.32}$$

Experiments on the intensification of the magnetic field by explosion were conducted at the Los Alamos Laboratory (USA) [7]. The source of the primary magnetic field B_0 was the pulse solenoid to which the capacitor bank was discharged. The solenoid was placed into a metal tube, which was equipped with a radial slot and an explosive surrounded by a ring.

When the capacitors were discharged, a magnetic flow appeared onto the solenoid in the tube, owing to the slot which freely penetrated through its walls. At the moment when the magnitude of the magnetic flow approached the maximum, the blasting of the explosive was produced. The metal cylinder was squeezed, and the slot in it collapsed. With further compression, the magnetic flow was "frozen" within the cylinder.

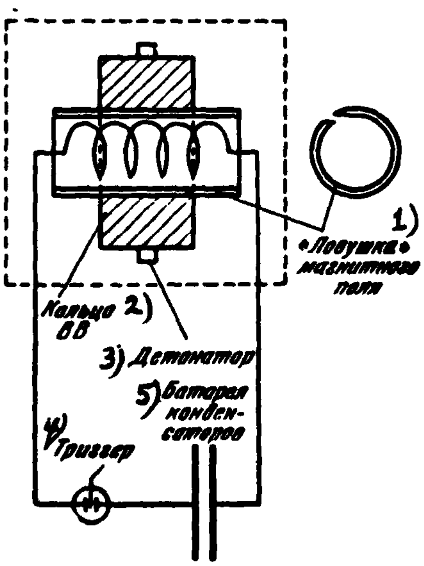


Fig. 67. Key: 1) "Trap" of magnetic field; 2) Ring of explosive; 3) Detonator; 4) Trigger; 5) Capacitor bank.

The strength of the achieved magnetic field was measured by the test coils and was oscillographed. As a rule, one of the the test coils was placed inside the metal cylinder and the other, outside it. The initial magnetic field was monitored according to the magnitude of the discharge current of the capacitor bank; a test coil of toroidal shape (Rogowski loop) was used as a current sensor. The process of explosion and compression of the conducting shell was recorded on film by means of a superhigh-speed movie camera. A diagram of the experiment is shown on Fig. 67. Parts of the apparatus surrounded on the diagram by a dashed line were destroyed by the explosion. A special triggering circuit was used for synchronization of the primary pulse magnetic field, movie camera and detonation.

In experiments depending on the magnitude of the inductive load, two banks of capacitors with identical working voltage of 20 kV were used. The first capacitor bank with a capacitance of 435 μF was designed for discharge on an inductance of the order of several hundreds of microhenries. It was charged from a source of dc voltage. The second bank with a capacitance of 290 μF was part of an artificial line, which was charged in a pulse mode from the first bank and through separate triggers was discharged on an inductive load of the order of several μH.

Twelve coaxial cables, connected in parallel, went from the capacitor bank to the solenoid. For a length of 2.5 m the cables were bronzed and ended with a plug-type connector. From the connector and further, for an extent of 1.5-2 m, up to the solenoid, the wires were destroyed by the explosion.

Several types of solenoids were used in the experiments: those wound with copper wire, Bitter spirals cut from brass, and single-turn coils. Solenoids designed for high values of the initial magnetic field were placed within the cut metal tube. A polyethylene insulating spacer 0.5 mm thick was used to protect from a breakdown between the solenoid and the tube. In order to reduce the reverse magnetic flux to a minimum, the solenoid was carefully fitted for the tube and compactly entered into it. The average value of the initial magnetic field was 100 kOe with an internal diameter of the solenoid of 7.5 cm and length of 7.5 cm. In some experiments the

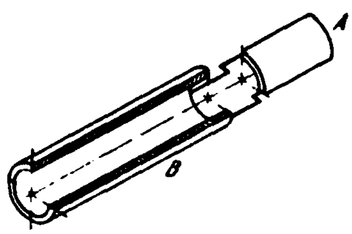
ıagnetic system consisting of two solenoids was used. One solenoid ıas placed inside and the other outside the ring of the explosive substance.

Tubes for capturing the magnetic flux ("trap") were made of copper, brass and also steel with a high specific electrical resistance. The average thickness of the walls near the traps was 3 mm with a diameter of 7.5-8 cm. The duration of the pulse of the magnetic field generated by the solenoid was of the order of 100 μs. Copper and brass are good conductors, and the magnetic flux weakly penetrates into them. Therefore, they are equipped with a slit, which converts the trap into a magnetic concentrator (see § 1 of this chapter). Steel traps freely pass the magnetic flux, since the resistance of the steel is considerably higher than that of copper or brass.

The slit in the trap was equipped with good insulation, since the voltage on it reached 2 kV. At the same time, the trap had to be "collapsed," as the compression caused by the explosion was just started. Good results were obtained when the standard insulation tape 0.2 mm thick was used as the insulation; the trap "admitted" the initial magnetic flux and "collapsed" with the explosion. The slit in the wall was not made radial but oblique, almost tangential. Such a slit was easily closed up with the explosion and decreased the resistance of the trap with compression. Steel traps were used without the slit. In spite of the high electrical resistance, steel with very small times of compression behaved as a good conductor. Therefore, it "captured" the magnetic flux well, and the thick-walled trap did this better than the thin-walled trap.

The effective area of the test coils was included in limits of 0.05-10 cm^2. The test coil was mounted on the end of the coaxial cable, which connects it with the integrator and oscilloscope placed in the bunker. The "half-loop" coil shown on Fig. 68 was most frequently used. The end of the coaxial cable was free of metallic braiding and was inserted into the brass tube with a slit along the length. The end of the central wire was soldered to the "half-loop" at point A, and the braiding was soldered to the brass tube at point B. All the slits in the "half-loop" were carefully filled with a

ecial glue. The gathered test coil was placed into the thin-walled ass tube, was turned above it by a double tape of insulation and pper foil soldered to the shield of the cable at one point, and ove everthing was once again insulated. The diameter of the sensor completely gathered form was included in limits of 7.5-10 mm. ch sensor was calibrated by the known magnetic field, and its ex-rimentally obtained constant was compared with the computed one. e integrators and amplifiers were also carefully calibrated. As a sult, the accuracy of the measurements of magnetic field consisted not less than 15%.



ig. 68.

The explosive charge had the shape of a cylinder with an inter-al diameter of 8 cm, an external diameter of 20-25 cm and a height f 4 to 10 cm. The detonators had the form of rings closely pressed o the external surface of the cylinder.

The superhigh-speed movie camera made photographs every 0.3-0.6 s. The movie frames recorded the dependence of the diameter of he trap on time in the explosion process. On the average the trap as squeezed from the initial diameter of 7.5-8 cm to the final iameter of 12 mm. The cloud of vapors and gases formed during the xplosion filled at some moment the field of view of the movie camera, nd the photographing was ceased.

Let us make estimates by means of simplified formulas, which haracterize the process of magnetic compression. From (10.33) it ollows that:

$$\frac{dB}{dt}=-2B(t)\frac{v}{R(t)}, \qquad (10.33)$$

here $v=\frac{dR}{dt}$ is the speed of movement of the wall of the trap. The angential electrical field

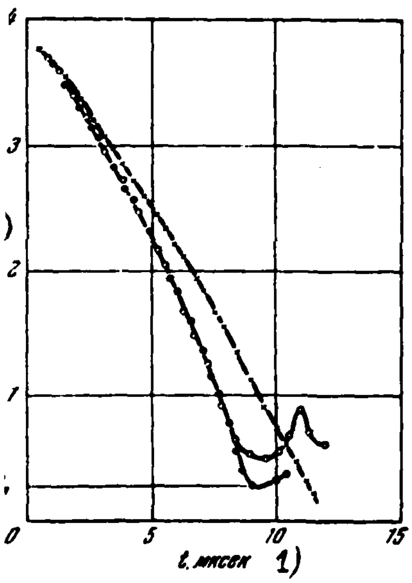
$$\oint_C \mathcal{E}_\varphi\, dl=\frac{\partial}{\partial t}\int_S B\,dS=B(t)\,v\,\frac{r}{R}. \qquad (10.34)$$

the outline C is the circle of radius r (radius of the test coil), ›n the induction emf is then equal to

$$\mathscr{E}=2\pi r^{2}B(t)\frac{v}{R}. \qquad (10.35)$$

Let us give some figures which are standard for the conducted ›eriments. The initial induction B_0=120 kG; the initial radius of › trap R_0=3.8 cm; the final radius of the trap R=0.5 cm; and the ›ed of movement of the wall $v=1.5\cdot 10^3$ m/s. Then from (10.30) it llows that B=6.9 MG.

With the final radius equal to 0.4 cm, $\mathscr{E}_{\varphi}=8.3\cdot 10^3$ V/cm, and › induction emf $\mathscr{E}$ =21 kV. The emf induced in the test "half-loop" il with a radius of 2 mm reaches 5.2 kV.



g. 69. Radius of the trap capturing the magnetic flux in the ex- osion as a function of time.

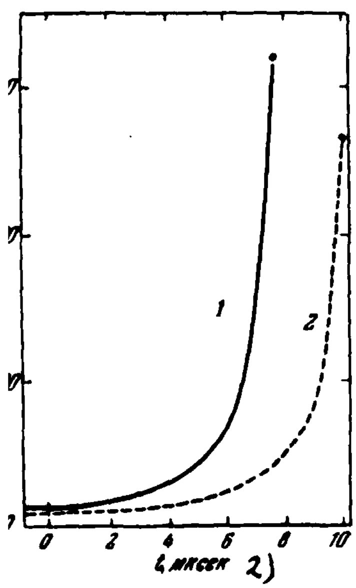
brass cylindrical trap with a wall thickness of 3 mm and outer di- eter of 7.5 cm. Explosive is packed by a ring with an internal ameter of 7.5 cm and external diameter of 20 cm. 0 - theory; - experiment; $R_в$ - return radius. Key: 1) μs; 2) cm.

Equations (10.30) and (10.34) completely describe the electrical d magnetic fields in the trap if the dependence of the radius and eed of movement of the wall on time is known. These dependences re approximately calculated [7] on a calculating machine for the oblem of the uniform (radially symmetric) explosion under the fol- wing simplifying assumptions: the absence of edge effects, magnetic

sure is guided along the normal to the moving wall, and the con- ivity is infinite. Results of the calculations and experimental obtained by means of a movie camera are compared on Fig. 69.

It is interesting to note that according to theory, there exists rtain critical return radius, which corresponds to the moment the pressure of the gases, which are formed during the explosion, mes equal to the magnetic pressure. Oscillations of the volume he trap should appear near the return radius (R_B on Fig. 69).

From the theory it also follows that the speed of movement of wall does not depend on the initial magnetic field and that the ıetic flux behaves as a gas in a closed volume with adiabatic com- ssion; the greater the initial magnetic field, the less the final ld, and the larger the return radius. At small initial magnetic lds, the magnetic energy closed in the trap can be increased a ısand times owing to the energy of the explosion.

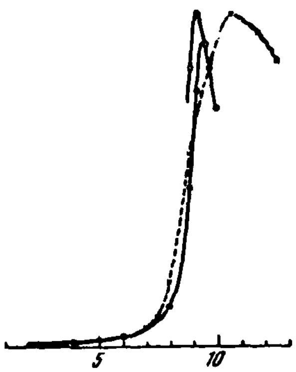


. 70. Time in a steel trap compressed by the explosion as a func- n of induction of the magnetic field. 1 - internal diameter of trap - 8 cm, thickness of walls - 1.5 mm, and time of growth of ial field - 130 s; 2 - internal diamter - 8 cm, thickness of ls - 3 mm, and time of growth - 160 s. Key: 1) kG; 2) μs.

Calculations show that it is possible to convert up to 15-20% the energy of the explosion into the energy of the magnetic field.

in theoretical and experimental results are given on Fig. 70 ig. 71. Figure 70 shows the growth of the integral voltage on est coil in the compression process of the trap. In order to the whole region of voltages, two coils with a different efve area were used.

Figure 71 compares the theoretical and experimental curves for xperiment in which the absolute record of the magnetic field gth, 14,300,000 Oe, was established.



71. Results of an experiment in which a magnetic field of 00 kOe was obtained. Solid line - calculation, dashed line - riment; ● - H_0=100 kOe; O - H_0=15 kOe; X - H_0=90 kOe.
1) MG; 2) μs.

The initial magnetic field strength in this experiment coned of 90 kOe, and the time of growth of the magnetic field from Oe to 14,300 kOe was 3.5 μs. Theoretical curves were calculated the two initial values of the magnetic field: 75 kOe and 100 kOe.

There is a certain divergence between the theory and experiment he time growth of the magnetic field strength. The theoretical is 2 μs less than the experimental time. This divergence is rently connected with the complex processes of the interaction he shock wave with the body of test coil at a moment near to passage of the return radius. (For this experiment the radius he test coil was a total of only 20% less than the return radius).

The series of experiments conducted in the range of initial ngths of the magnetic field of 25-100 kOe confirmed the basic

positions of the theory. The study of the capture of fields with a small initial strength was limited by the minimal practically feasible radius of the test coil, taking the dimensions of its protective covering into account. In the majority of the experiments, this radius equaled 2.3 mm. As the experiments showed, the return radius for the initial field strength of 50 kOe is less than 2.3 mm. The signal with the test coil was broken when the magnetic field did not yet reach the maximal value. The same effect was observed at smaller initial voltages of the magnetic field. In the course of the experiments, the brass and copper traps behaved identically.

Theoretically, in the explosion method the maximal value of the achievable magnetic field does not exist. In order to exceed the achieved results, it is necessary to increase the volume occupied by the initial magnetic field and to increase its strength.

Besides magnetic traps of cylindrical shape, we investigated magnetic traps of another shape, in particular, with square and triangular cross sections. In this case the solenoids are located on the outside. In the triangular trap, the magnetic field strength grew more rapidly than that in the square trap, since with the same magnitude of the line movement of the wall, the area of the triangle is decreased more rapidly than the area of the square.

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